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A 4.8 HOUR PERIODICITY IN THE SPECTRA OF CYGNUS X-3

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ABSTRACT

The X-ray binary Cyg X-3 has been observed on three occasions during 1975 and 1976 by the GSFC Cosmic X-Ray Spectroscopy Experiment on *OSO 8*. The X-ray spectra from all three observations can be represented by power-law continua with strong iron line emission. Comparisons of spectra taken within the same observation at various phases of the 4.8 hour period reveal a relative excess of low-energy X-ray emission near zero phase (i.e., the minimum) of the 4.8 hour modulation. In addition, the centroid of the line emission is observed to vary in phase with the 4.8 hour cycle. The possibility of persistent thermal X-ray emission from material surrounding the binary system is introduced in an effort to account for the observed effects.

Subject headings: X-rays: binaries — X-rays: spectra

I. INTRODUCTION

The 4.8 hour nearly sinusoidal variation in the intensity of Cyg X-3, which was first observed by Parsignault *et al.* (1972), has often been attributed to the motion of a compact object in a binary system (Basko, Sunyaev, and Titarchuk 1974; Pringle 1974; Davidsen and Ostriker 1974; Milgrom 1976). Proposed models for Cyg X-3 are similar in that they all require substantial scattering of the emitted X-rays within the binary system. Stellar wind models (for example, Davidsen and Ostriker 1974) predict that the spectrum of Cyg X-3 should vary in phase with the 4.8 hour cycle. Although the spectrum of Cyg X-3 has been known to vary markedly over time scales long compared to 4.8 hours (Leach *et al.* 1975; Serlemitsos *et al.* 1975), previous observers have failed to detect any variability in the spectrum over the 4.8 hour cycle (Parsignault *et al.* 1972; Leach *et al.* 1975; Parsignault *et al.* 1977; Sanford, Mason, and Ives 1975). The independence of the spectra with respect to binary phase led Milgrom (1976) to propose a "cocoon" model for Cyg X-3.

II. OBSERVATIONS AND RESULTS

The GSFC Cosmic X-ray Spectroscopy Experiment on *OSO 8* (CXSE) observed Cyg X-3 in 1975 November, 1976 May, and 1976 November, each observation lasting 1–3 weeks. During all three observations Cyg X-3 was in a low-intensity state, with the 2–10 keV intensity between 2.5–2.7 $\times 10^{-9}$ ergs cm^{-2} s^{-1} at phase 0.5. The experiment consists of two xenon detectors each with 5° FWHM fields of view (the A and C detectors) and one argon detector having a 3° FWHM field of view (the B detector). The xenon and argon detectors have energy ranges of 2–60 keV and 2–25 keV, respectively. The three detectors are described in Becker *et al.* (1976, 1977) and Pravdo *et al.* (1976).

All the observations revealed the well-known 4.8 hour intensity variations in phase with the recent ephemeris of Parsignault *et al.* (1977) as illustrated in Figures 1*a* and 1*b*. In order to study the nature of the X-ray emission as a function of phase in the 4.8 hour cycle, we folded the data within each single observation modulo 4.8 hours into 20 bins. This seemed justified insofar as no significant day-to-day variations in source intensity or spectrum were observed within any single observation. Simple spectral models were fitted to data at each phase of the 4.8 hour cycle for each observation. To facilitate comparisons, the fits were restricted to 2–25 keV for all three detectors.

The best fits for a single component model were obtained with a power law modified by photoelectric absorption and strong iron line emission (EW $\approx$ 1800 eV). These models did not give acceptable fits, but qualitatively they describe the data well (as seen in Figs. 2*a* and 2*b*, where the reduced χ^2's are 1.7 and 3.6, respectively), except that they may overestimate the contribution from the line. Thermal bremsstrahlung and blackbody continua always yielded substantially higher values of χ^2 (typically χ^2 increased by over 100 for 52 degrees of freedom). If we considered only the energy range of 2–10 keV, the data could be fitted in many cases by a blackbody continuum of $kT \approx 2$ keV. These fits also required the presence of an iron line, but the equivalent width was down by about a factor of 2 from the estimate given by the power law fits (see Figs. 1*e* and 1*f*). We expect that the actual value of the equivalent width is intermediate between these two extremes. Over the limited energy range of 2–10 keV it is difficult to distinguish between power-law and blackbody continua, but above 10 keV the blackbody

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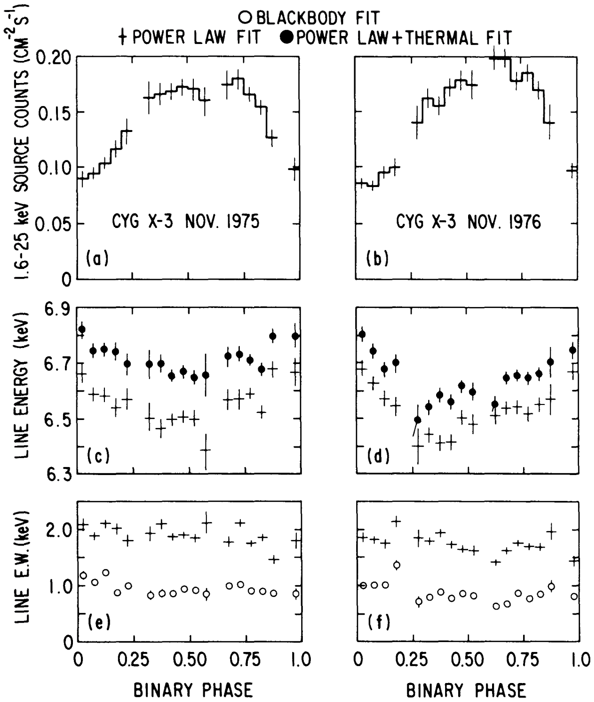

FIG. 1.—(*a, b*) The phase dependence of the X-ray intensity from Cyg X-3 in Nov. of 1975 and 1976 respectively. (*c, d*) The phase dependence of the centroid of the line emission for power-law continua and for power-law plus thermal bremsstrahlung continua. The values for a blackbody continuum are similar to those for the power-law continuum. Errors are 1 σ estimates as described in Table 1. (*e, f*) The phase dependence of the equivalent width of the line emission for power-law continua and for blackbody continua. Other continuum models yielded intermediate values for the equivalent width. Errors are 1 σ estimates as described in Table 1.

model cannot even qualitatively represent the observed spectra.

Since data taken with the argon detector have finer pulse height binning between 2 and 25 keV, we will give the numerical values found for them. At the top of Figure 2, we present two representative pulse-height spectra for phases 0.0 and 0.5 of the 4.8 hour cycle, along with the best fit power law continuum for each spectrum as given in Table 1. At the bottom of Figure 2, we show the inferred incident spectrum for both phases. These incident spectra were derived using spectrum-dependent detector efficiencies based on the power-law fits given in Table 1. We can summarize the results of the power-law fits from both observations of Cyg X-3 as follows:

1. The spectra at phase 0.0 tend to be flatter (i.e., have a lower spectral index) with lower neutral hydrogen column densities than the spectra at phase 0.5. This variation is due primarily to changes occurring below 8 keV. Above 8 keV the spectra appear similar.

2. The equivalent width of the iron line feature appears to be phase independent, with values of 1600–2000 eV (see Figs. 1*e*, 1*f*).

3. The iron line feature is broadened, with a FWHM of ~1 keV.

4. The centroid of the iron line feature shifts ~0.2 keV in phase with the 4.8 hour cycle, with its center at 6.7 and 6.5 keV at phase 0.0 and 0.5 respectively (see Figs. 1*c*, 1*d*).

The xenon detector observations show the same relative phase dependence. Since these simple continuum fits are not acceptable, changes in N_H and α cannot be interpreted directly as changes in the column density or any other physical parameter, but they are indicative of changes in the spectral shape of the X-ray emission.

Although the simple power-law continuum models are fair representations of the data, they are not sensitive to possible spectral changes over restricted energy ranges. In order to display the spectral difference between the two extreme phases of the 4.8 hour cycle in a model-independent way, we have taken the ratio of the two spectra channel by channel for both the 1975 November and 1976 November data sets. These are plotted in Figure 3. If the two spectra were identical, their ratio would be constant and equal to the ratio of the overall intensity. A ratio of unity would imply that there is no 4.8 hour modulation. From Figure 3, we see that above 8 keV the spectra from phase 0.0 and 0.5 are consistent with each other (i.e., the ratios are nearly constant). However, below 8 keV they differ markedly. To summarize these differences, we see that (1) there is a relative excess of emission at 6.8 keV in the phase 0.0 spectrum; (2) there is a relative deficit of emission between 4 and 6 keV in the phase 0.0 spectrum; and (3) there is a relative excess of emission below 4 keV in the phase 0.0 spectrum. In other words, there is a decrease in modulation at 6.8 keV and below 4 keV, and an increase in modulation between 4 and 6 keV.

These differences between the spectra at phases 0.0 and 0.5 suggest an interpretation in terms of two separate components of X-ray emission. Fitting the continuum with a thermal bremsstrahlung component with $kT \approx 3$ keV or a blackbody component of $kT \approx$

TABLE 1

SIMPLE SPECTRAL FITS TO CYGNUS X-3 IN 1976 NOVEMBER*
(2–25 keV power-law models)

Parameter.	Phase 0.0	Phase 0.5
Norm	0.158	0.465
Spectral number index	1.326±0.03	1.438±0.02
N_H(atoms cm^{-2}).......	3.2±0.2×10^{22}	5.7±0.2×10^{22}
Iron line energy (keV)	6.68±0.03	6.50±0.02
Equivalent width (eV)	1695±85	1500±75
Line photons (cm^{-2} s^{-1})	0.0275±0.0013	0.0577±0.0030

* Errors given are generated from an automated modification of the CURFIT subroutine described in Bevington 1969. This program yields estimates of errors in fitting parameters, which are close to 1 σ errors whenever the "curvature" search option is used (Marquardt 1963). This procedure is mathematically identical to allowing χ^2 to increase by unity.

1.2 keV plus a power law of number index ~1.5, with the strength and absorption of each allowed to vary with phase, significantly reduces the χ^2 of the fit compared to the simple power-law model. The average reduction of χ^2 is 37 for 51 degrees of freedom. The power-law component is modulated by a factor of 2 over the 4.8 hour period and is modified by a varying amount of photoelectric absorption, with the highest absorption occurring at X-ray minimum. Hence, there is an increased modulation at low energies (<6 keV). Superposed on the power-law component, there is a low-energy component, which can be represented by either a thermal bremsstrahlung or a blackbody continuum, which undergoes significantly less modulation over the 4.8 hour cycle. If this second component is thermal in nature, it would contribute iron line emission at 6.7 keV, resulting in the relative excess observed near that energy.

In practice, we cannot determine independently for this model the temperature of the low-energy component, the absorption for this component, or the absorption for the power-law component. Our best estimate for the temperature of the low-energy, thermal bremsstrahlung component is 3 ± 0.6 keV modified by an equivalent column density of hydrogen N_H of $5 \pm 1 \times 10^{22}$ cm^{-2}, where the errors are 1 σ as deduced from the scatter of best fits from a number of independent data sets. Similarly the best estimate for the spectral number index is 1.54 ± 0.10 for the power-law component, with absorption due to N_H varying from

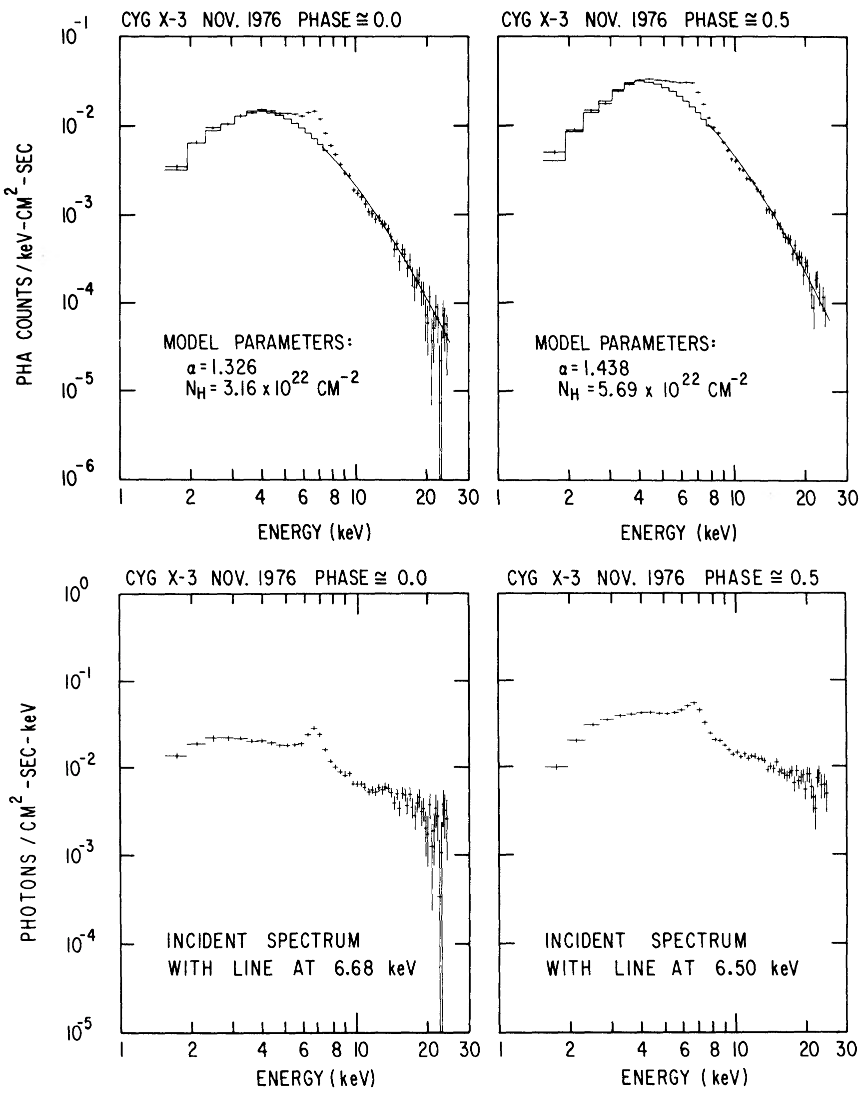

FIG. 2.—*Top*, the pulse-height spectra for phases 0.0 and 0.5 of the 4.8 hour period of Cyg X-3 during 1976 November with the best-fit power-law continuum superposed for comparison. *Bottom*, the inferred incident photon spectra corresponding to the two pulse-height spectra.

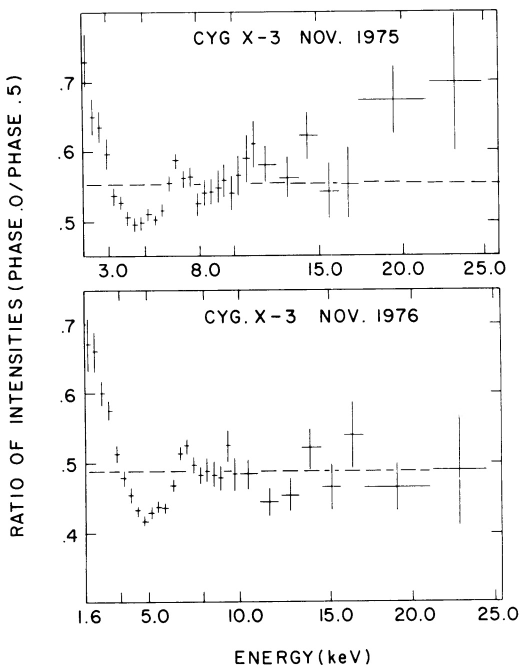

FIG. 3.—Ratios of the PHA spectra of Cyg X-3 accumulated at phases 0.0 and 0.5 of the 4.8 hour period during 1975 November and 1976 November.

2.5×10^{23} cm^{-2} to 1.2×10^{23} cm^{-2} for the minimum and maximum of the 4.8 hour cycle, respectively. This model implies an X-ray intensity between 1.5 and 6 keV of $5\text{–}10 \times 10^{-10}$ ergs cm^{-2} s^{-1} in the low-energy component.

The energy of the iron line determined with a two-component continuum model is also seen to vary with binary phase, as shown in Figures 1*c* and 1*d*. In this representation, the best fit equivalent width is ~1.3 keV. If the low-energy component is thermal in nature, we would expect it to contribute approximately 0.3 of the line emission observed at phase 0.0, for material of solar composition (based on work by Raymond and Smith 1977).

III. DISCUSSION

The failure of previous observations of Cyg X-3 to reveal any spectral dependence and, in particular, any dependence of photoelectric absorption on the 4.8 hour cycle, led previous authors to dismiss a stellar wind model for Cyg X-3 (Milgrom 1976; Hertz, Rappaport, and Joss 1977; Parsignault *et al.* 1977). In order to circumvent this difficulty, Milgrom proposed a shell model to explain the behavior of Cyg X-3. The shape of the 4.8 hour light curve of Cyg X-3 implies that the X-rays are being scattered through a cloud with an optical depth to Compton scattering of at least unity (Hertz, Rappaport, and Joss 1977). If this material were distributed throughout the binary system, there would be a large increase in photoelectric absorption at phase 0.0 relative to phase 0.5. Milgrom pointed out that if all the scattering material were arranged in a shell, the photoelectric absorption would be less dependent on binary phase.

Our observations clearly indicate that there is a spectral dependence on the 4.8 hour period when Cyg X-3 is in a low intensity state. Furthermore, they are consistent with a large increase in photoelectric absorption at phase 0.0 for a presumed power-law component which might logically be associated with the compact object. This increased absorption is hidden by the presence of the low-energy component so that experiments with lower resolution would not have observed the effect. The observed change in N_H over the 4.8 hour period is ~0.6 that derived from calculated spectra by Hertz, Rappaport, and Joss (1977) for a neutral stellar wind model (model 2C, $\Upsilon = 2$). Therefore, we conclude that stellar wind models for Cyg X-3, such as proposed by Davidsen and Ostriker (1974), are still a viable description of the Cyg X-3 binary system.

If Cyg X-3 is at a distance of 10 kpc, the low-energy component has an X-ray luminosity of $\geq 5 \times 10^{36}$ ergs cm^{-2} s^{-1} between 1.5 and 6 keV. For a uniform-density emission region at $kT = 3$ keV, this implies $N_e{}^2V \geq 2 \times 10^{59}$ cm^{-3}, where V is the volume of the emission region and N_e is the electron density. As an example, if $N_e = 10^{12}$ cm^{-3} and if the emission region is spherical, the radius R of the emission region is $\geq 4 \times 10^{11}$ cm. Such a region is comparable in size to the binary orbits of low-mass X-ray binaries.

A low-energy, constant component could also result from the presence of an additional unresolved source of X-ray emission unrelated to Cyg X-3. Shulman *et al.* (1975) and Davidsen *et al.* (1977) have presented evidence for such a source, Cyg X-7. However, their source is of too low a temperature and too weak to account for the low-energy component we observe. In any event, the possibility of an additional source would not change our conclusion that the power-law component from Cyg X-3 undergoes increased photoelectric absorption near minimum.

If there are two continuum components, there could be two components of iron line emission: a thermal component at 6.7 keV, and also a fluorescent line at 6.4 keV resulting from X-rays from the power law which excite cool material within the binary system. Since the fluorescent line would vary in intensity with the power-law emission, the relative strength of the two line components would vary, resulting in the observed 0.2 keV shift of the line profile with binary phase. The measured equivalent width depends strongly on the assumed continuum, varying by a factor of 2 among different models; but whatever the absolute value of the equivalent width, there are several measurements which show it to be independent of binary phase (Sanford, Mason, and Ives 1975; this paper). If there are two competing line components, the near constancy of the equivalent width may be a coincidence. If the equivalent widths of the line emission associated with each continuum component are equal, then the total equivalent width will be independent of the relative strengths of the components.

The discovery of a spectral dependence for the X-ray emission from Cyg X-3 with binary phase resolves a long-standing difficulty with stellar wind models for this system. Our observations, although conclusive, are incomplete because they deal only with the low state of Cyg X-3. Serlemitsos *et al.* (1975) have shown that the spectrum of Cyg X-3 is radically different when in a high state. A sensitive search for a spectral dependence with phase when Cyg X-3 is in a high state is required before a complete picture of this complex binary system can be drawn.

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